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A targeted survey for H I clouds in galaxy groups

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ABSTRACT

Five galaxy groups with properties similar to those of the Local Group have been surveyed for H I clouds with the Arecibo Telescope. In total 300 pointings have been observed on grids of approximately $2.5 \times 1.5 \text{ Mpc}^2$ centred on the groups. The 4.5σ detection limit on the minimal detectable H I masses is approximately $7 \times 10^6 M_\odot$ ($H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$). All detections could be attributed to optical galaxies; no significant detections of H I clouds have been made. This null result leads to the conclusion that the total H I mass of intragroup clouds must be less than 10 per cent of the total H I mass of galaxy groups and less than 0.05 per cent of the dynamical mass. The recent hypothesis that Galactic high-velocity clouds are Local Group satellite galaxies is highly inconsistent with these observations.

Key words: ISM: clouds – intergalactic medium – Local Group – galaxies: luminosity function, mass function – radio lines: ISM.

1 INTRODUCTION

Groups of galaxies have been the subject of many H I studies. Well known H I maps of, for example, the M81 group (van der Hulst 1979; Appleton, Davies & Stephenson 1981; Yun, Ho & Lo 1994) show that these groups often host tidal H I features (see also e.g. Haynes, Giovanelli & Chincarini 1984 for a review; van Driel et al. 1992; Li & Seaquist 1994; Rand 1994). The incidence of H I features was quantified by Haynes (1981) who found that six galaxy groups from a sample of 15 show H I appendages from at least one member galaxy. These data might suggest that H I filaments and intragroup clouds are common throughout galaxy groups, but such a conclusion could be misleading since H I surveys are normally concentrated on the inner parts of galaxy groups and often on interacting pairs within the groups. Systematic searches throughout the volumes occupied by the groups are rare because the projected sizes of groups in the sky are too large to be covered by aperture synthesis instruments. A notable exception is the survey described by Lo & Sargent (1979) who systematically searched for H I clouds throughout the volumes around the M81, CVnI and NGC 1023 groups. No clouds were detected to the H I mass limit of $4 \times 10^7 M_\odot$, although several new dwarf galaxies were discovered.

Lo & Sargent (1979) discussed their null result in the context of Galactic high velocity Clouds (HVCs). They concluded that HVCs are unlikely to be intergalactic gas clouds in the Local Group (LG) because then they should have detected an equivalent population in the external groups. Similar conclusions were reached by

Giovanelli (1981) and Wakker & van Woerden (1997). However the idea that the HVCs, instead of being small clouds close to the Milky Way galaxy, are clouds of primordial composition at LG distances has recently seen a revival. Originally proposed by Oort (1966), and subsequently discussed by Verschuur (1969) and Hulsbosch (1975), the idea has been refined by Blitz et al. (1999, hereafter BSTHB), who added a dark-matter component to the clouds. The problem with the earlier considerations of the extragalactic origin of HVCs was their derived distance. Hulsbosch (1975) concluded on the basis of the virial theorem that typical distances would be approximately 10 Mpc, which places the clouds outside the LG. BSTHB show that if the HVCs are built from the same material that the galaxies are made of (typical baryon content f_B of 10 per cent), their distances would reduce to $\sim 1 \text{ Mpc}$. Moreover, they show that the distribution of the clouds in the sky resembles that of LG dwarfs and their kinematics, as an ensemble can be well modelled if they are distributed throughout the LG. Braun & Burton (1999, hereafter BB) define a subsample of 65 compact HVCs and come to essentially the same conclusion about their subsample. Note that the BSTHB and BB models do not apply to the HVCs associated with the Magellanic Stream, which are likely the result of tidal interactions between the Milky Way and the Magellanic Clouds (Putman et al. 1998).

Placed at LG distances, the HVCs have H I masses of $\sim 3 \times 10^7 M_\odot$ and typical diameters of 30 kpc. In this picture, approximately 500–1000 clouds are distributed throughout the LG, together adding approximately $4 \times 10^{10} M_\odot$ to the LG H I mass. Interestingly, this number of HVCs is in reasonable agreement with the number of mini haloes that are predicted by numerical simulations of the hierarchical LG formation (Klypin et al. 1999; Moore et al. 1999). Corrected for incompleteness, the BB sample comprises of ~ 100 clouds. Using the updated average distance of

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Table 1. Properties of surveyed groups.

(1) Name	(2) α_{2000} (h min)	(3) δ_{2000} (° arcmin)	(4) N_m	(5) $\langle v \rangle$ (km s ⁻¹)	(6) σ_r (km s ⁻¹)	(7) $\log L_B$ ($h_{65}^{-2} L_\odot$)	(8) $\log M_{H I}$ ($h_{65}^{-2} M_\odot$)	(9) $\log M_{dyn}$ ($h_{65}^{-1} M_\odot$)	(10) R_0 (h_{65}^{-1} Mpc)
NGC 5798	14 56	30 21	3	1773	40	9.9	9.5	12.0	0.9
NGC 5962	15 35	15 26	5	1872	126	10.8	10.0	13.0	1.9
NGC 5970	15 37	12 14	4	1887	58	10.7	10.1	12.3	1.2
NGC 6278	17 00	23 02	3	2911	104	10.5	9.6	12.8	1.7
NGC 6500	17 53	18 16	6	2994	105	11.0	10.2	13.3	2.3
NGC 6574	18 12	13 37	4	2279	28	10.9	10.2	12.2	1.1
LG			3 ^a		61 ^b	10.6 ^c	10.1 ^d	12.4 ^b	1.2 ^b

(1) Most luminous member. (2) and (3) Unweighted average RA and declination. (4) Number of known members with measured redshifts. (5) Unweighted average radial velocity. (6) Radial velocity dispersion: The uncertainty on this is approximately $\sigma_r/\sqrt{N_m}$. (7) Integral *B*-band luminosity. (8) Integral H I mass. (9) Rough estimate of dynamical projected mass (see text). (10) Estimate of the ‘zero-velocity radius’ (see text).

^aNumber of LG members included in the Garcia (1993) catalogue if the LG were to be at a distance of 30 Mpc.

^bTaken from Courteau & van den Bergh (1999).

^cTaken from van den Bergh (2000).

^dDwarfs from Mateo (1998) and giants from van den Bergh (2000).

650 kpc (Braun & Burton 2000), the total H I mass in their clouds would be approximately $10^9 M_\odot$.

Charlton, Churchill & Rigby (2000) show that the statistics of Mg II and Lyman limit absorbers in the spectra of quasars are in conflict with the hypothesis that the HVCs are intragroup material (see also Zwaan 2000). For analogous HVC populations to exist around intervening galaxies and in the LG, the typical distances would need to be less than 200 kpc from the LG barycentre. A very similar conclusion has been reached by Zwaan & Briggs (2000) who show that existing H I surveys impose strong constraints on the existence of extragalactic HVCs. If H I clouds exist in other groups or around galaxies, with properties similar to those proposed for the LG, several instances should have already been detected in large H I surveys such as the Arecibo Survey discussed by Zwaan et al. (1997).

In this paper, we present additional evidence by means of a targeted survey of five galaxy groups with the Arecibo Telescope. The selection of the targets is discussed in Section 2 and the data acquisition and analysis is summarized in Section 3. In Section 4 the detections are presented, and in Section 5 we discuss the implications on the existence of intragroup H I clouds. To enable a direct comparison between the surveyed groups and the LG, we adopt distances for the groups based on their redshift velocities and a Hubble constant of $H_0 = 65 h_{65} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 SAMPLE SELECTION

In order to make the targeted survey for H I clouds most efficient, we have selected the galaxy groups according to the following criteria: (1) The distance for the groups must be such that the expected H I cloud diameters match the projected extent of the Arecibo beam. BSTHB estimate that the cloud diameters are approximately 30 kpc. The 3 arcmin beam of the Arecibo Telescope subtends $d_{\text{beam}} = 0.87D$ kpc at a distance of D Mpc. The optimal group distance at which the clouds fill the beam is therefore 30 Mpc. We have selected groups with radial velocities in the range of $\sim 1800\text{--}3000 \text{ km s}^{-1}$. (2) The declination must be in the range of 10° to 30° so that the groups are accessible to the Arecibo Telescope and can be tracked for at least one hour. (3) To enable comparison with the LG, the global properties of the groups, such as the integral H I mass, luminosity, and dynamical mass, must be comparable to those of the LG.

The list of galaxy groups compiled by Garcia (1993) was found to be the most successful in meeting the above listed criteria. This catalogue was compiled from the LEDA¹ galaxy sample, and is basically a cross-section of groups found via a percolation method (Huchra & Geller 1982) and groups identified via the hierarchical clustering method (Materne 1978). Table 1 gives the measured and derived properties of the selected groups. The groups are named after their brightest member.

We have made crude estimates of the dynamical masses of the groups by applying the ‘projected mass estimator’ which is discussed by Heisler, Tremaine & Bahcall (1985) and is defined as

$$M_{\text{PM}} = \frac{32/\pi}{G(N_m - 1.5)\sum_i V_i^2 R_i}, \quad (1)$$

where N_m is the number of members, V_i is the radial velocity of member i with respect to the group mean velocity, and R_i is the projected distance of member i from the centre of the group. Since the groups have only three to six identified members, the errors on the mass estimates are large (approximately $M_{\text{PM}}/\sqrt{N_m}$). The radius of the zero-velocity surface, R_0 , beyond which galaxies participate in the Hubble expansion, can be calculated via (Sandage 1986)

$$R_0 = \left(\frac{8GT^2}{\pi^2} M_{\text{dyn}} \right)^{1/3}, \quad (2)$$

where T is the age of the group. We consider the ages of all groups to be 14 Gyr.

For comparison, we also give in Table 1 the most recent published properties of the LG, taken from Mateo (1998), Courteau & van den Bergh (1999) and van den Bergh (2000). For the LG, the dynamical mass is estimated using the virial theorem, but it has been shown by Heisler et al. (1985) that the virial theorem and the ‘projected mass estimator’ give very similar results. It is evident from the table that the selected groups have properties not very dissimilar from those of the LG; the selected groups are on an average equally gas rich, luminous, and massive and have a similar radial extent as the LG. Note that the centres of the NGC 5962 and 5970 groups are only $1.6 h_{65}^{-1} \text{ Mpc}$ apart and that their formal

¹We have made use of the Lyon-Meudon Extragalactic Database (LEDa) supplied by the LEDA team at the CRAL-Observatoire de Lyon (France).

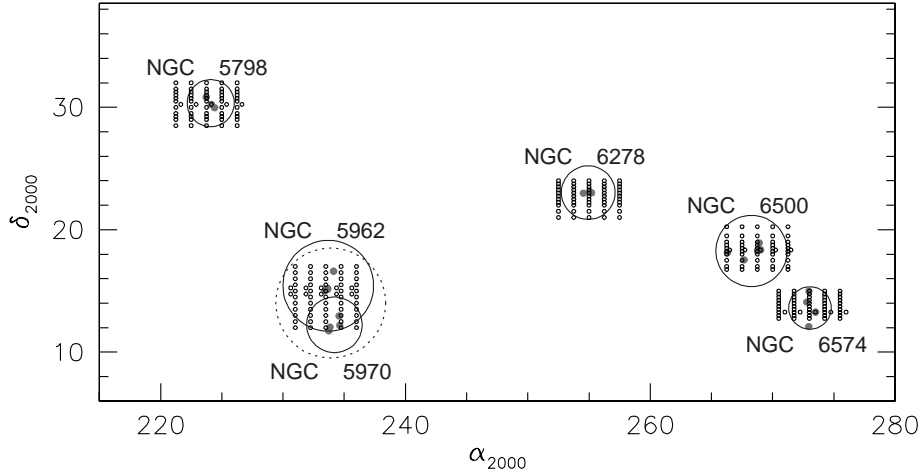


Figure 1. Positions of groups and pointings in the sky. The grey dots represent the individual galaxies in the groups, the big circles show the surfaces of zero gravity. These are typically 1–2 Mpc. For the NGC 5962 and 5970 groups their joint surface of zero gravity is also indicated. The groups are named after their brightest members.

zero-velocity radii are overlapping. Their difference in v_{hel} is only 15 km s^{-1} . It is suggestive that these two groups actually form one gravitationally bound system. If we assume that they form one group, its dynamical mass would become $\log M_{\text{dyn}} = 13.2 - \log h_{65}$, and its zero-velocity radius would be $2.3 h_{65}^{-1} \text{ Mpc}$. In the remainder of this paper we regard the NGC 5962/5970 group as one group.

3 OBSERVATIONAL STRATEGY

Observations were carried out with the refurbished Arecibo² Telescope during five nights in the period from 1999 April 18 until 1999 April 24 and on 1999 June 8 and 1999 June 9. The data were obtained with the L-narrow Gregorian receiver which has a measured system temperature of 32 K, and a gain of 10 K Jy^{-1} . Spectra of 2048 channels were recorded for two polarizations over a bandwidth of 12.5 MHz, centred on the frequency of the 21-cm line redshifted to the mean velocity of each galaxy group. This setting results in a total velocity coverage of $\sim 2600 \text{ km s}^{-1}$ and a velocity resolution of 1.3 km s^{-1} before Hanning smoothing. Spectra were dumped every 60 s.

The pointings were arranged in rectangular grids centred on the galaxy groups. The grids were built from several series of five pointings on lines of constant declination, where each pointing was separated by 5 min in an hour angle. The integration time per pointing was 4 min and integrations were separated by exactly 5 min in time. The remaining 1 min was used to slew the telescope back. This strategy insures that the same path on the telescope dish was traced during each of the five pointing in a series. No separate OFF scans were taken, but for each scan a synthetic OFF scan was computed by averaging the other four scans in the same series. This synthetic OFF scan y_j can be written as

$$y_j = \frac{N\bar{x} - x_j}{N-1}, \quad (3)$$

where N is the number of pointings in an array, x_j is an individual scan and \bar{x} is the average of all scans in one series.

²The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by the Cornell University under a cooperative agreement with the National Science Foundation.

For this type of observation, the observing technique is superior in its efficiency compared to a traditional observing scheme where separate ON/OFF pairs are considered for each pointing. For this ON/OFF scheme the total noise depends on the integration time as $\sigma \propto \sqrt{1/T_{\text{ON}} + 1/T_{\text{OFF}}}$. Normally, the integration times for the ON and the OFF scans are taken to be equal so that $\sigma \propto 2/\sqrt{T_{\text{tot}}}$, where $T_{\text{tot}} = T_{\text{ON}} + T_{\text{OFF}}$ is the total integration time needed for each pointing. According to our strategy, where we make composite OFF scans from other scans in the array, the noise $\sigma' \propto \sqrt{1/T'_{\text{tot}} + 1/([N-1]T'_{\text{tot}})}$, where N is the number of pointings in one series and T'_{tot} is the time spent on each pointing. From this we can derive

$$\frac{T_{\text{tot}}}{T'_{\text{tot}}} = \frac{4(N-1)\sigma^2}{N\sigma'^2}. \quad (4)$$

This shows that in our case, where $N = 5$, the technique is 3.2 times faster than traditional ON/OFF procedures, yielding a 1.8 times higher signal-to-noise ratio in a given amount of time.

Fig. 1 shows a schematic view of the pointings that were observed, together with the positions of the group galaxies. The circles indicate the sizes of the groups characterized by the zero-gravity radius R_0 . The grids of pointings sparsely sample rectangular areas of approximately $2.5 \times 1.5 \text{ Mpc}^2$.

Calibration of the data was performed by observing continuum sources with known flux densities. Separate scans and polarizations were averaged and Hanning smoothed. Polynomials were fitted to regions free from obvious signals, and subtracted from the spectra in order to obtain flat baselines. A first-order polynomial (linear baseline) was generally found to be sufficient. Each spectrum was then Gaussian smoothed to resolutions of 5, 10, 25 and 50 km s^{-1} . The resulting noise level was on average 0.75 mJy at 10 km s^{-1} resolution, which corresponds to a minimal detectable H I column density level of $1.2 \times 10^{18} \text{ cm}^{-2}$ (4.5σ). The lowest detectable H I mass at 30 Mpc was $7.1 \times 10^6 M_{\odot}$ for a 10 km s^{-1} broad signal. The H I mass limit increases to $1.6 \times 10^7 M_{\odot}$ for signals 50 km s^{-1} wide.

All spectra were checked for the 4.5σ peaks in the full resolution and the smoothed spectra. The list of 4.5σ peaks was first checked for false positives due to radio frequency interference (RFI) by re-analysing the separate 60 s scans for both polarizations. All peaks that could not be unambiguously

attributed to RFI were re-observed for confirmation on 1999 June 8 and on 1999 June 9. The new observations were conducted following an ON/OFF fashion, spending 8 min ON and 8 min OFF on each position. The resulting noise level for these observations was therefore a factor 0.89 lower than that of the original observations carried out in 1999 April.

4 THE DETECTIONS

Three pointings were deliberately aimed at the positions of known galaxies. This was done to check the positional accuracy of the pointing method, and to obtain a confirmation of the flux calibration. The left three panels of Fig. 2 show the spectra of NGC 5789, UGC 11168 and NGC 6500. NGC 6500 shows a secondary peak at $\sim 3500 \text{ km s}^{-1}$. This turns out to be part of the H I filament in the galaxy pair NGC 6500/6501, that has been mapped with the Westerbork Synthesis Radio Telescope (WSRT) by van Driel, Davies & Appleton (1988). The authors describe the H I structure as a ‘classical bridge and tail configuration of a double galaxy interaction’. This is obviously of tidal origin, and is not a primordial H I cloud.

The right panels of Fig. 2 show the three other confirmed detections. The first one is due to UGC 11037. This galaxy was not

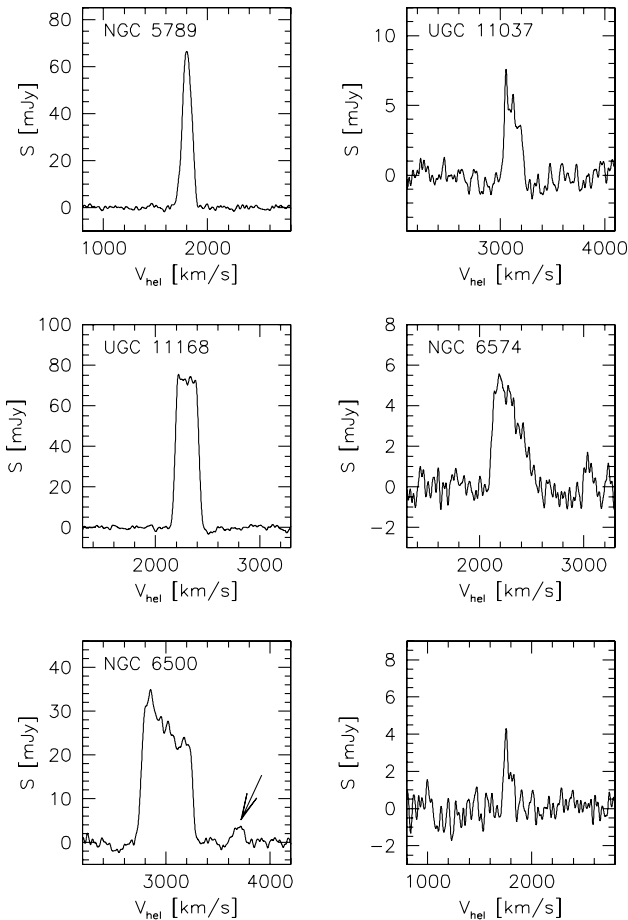


Figure 2. ‘Detections’ in the Arecibo Group Survey. The left three spectra are the result of pointings aimed at known galaxies. The secondary peak in the spectrum of NGC 6500 is caused by a known filamentary H I structure in the NGC 6500/6501 pair. The upper right and middle right are serendipitous detections of known galaxies. The lower right spectrum is probably the result of a nearby optical galaxy. All spectra are smoothed to an effective resolution of 15 km s^{-1} .

intentionally pointed at, but one of the pointings happened to fall very close ($\sim 1.3 \text{ arcmin}$) to this galaxy. There is a similar explanation for the detection in the spectrum in the central right panel. This pointing was only 2.6 arcmin separated from the centre of NGC 6574. The redshift of the signal agrees very well with the measured redshift of NGC 6574.

Finally, the lower right spectrum shows a detection at $15^{\text{h}}39^{\text{m}}00^{\text{s}}$, $12^{\circ}30'00''$ (α, δ) in the direction of the NGC 5962/5970 group. There is no catalogued galaxy at this position, but there is an obvious optical galaxy visible on the Digital Sky Survey (DSS), only 3 arcmin to the north. The observed H I redshift is consistent with the membership in the NGC 5962/5970 group. From the DSS we estimate the brightness of the galaxy to be $m_B = 17$ (assuming $B - V = 0.5$). The number density of galaxies brighter than $m_B = 17$ is approximately 4.0 per square degree (Metcalf et al. 1995). The probability of encountering a galaxy of such brightness within a 3 arcmin radius is therefore approximately 3 per cent. Furthermore, the velocity width of the signal is $150 \pm 15 \text{ km s}^{-1}$, a factor of ~ 7 larger than the typical width of the HVCs in the Wakker & van Woerden (1991) catalogue, and broader than any known HVC. We therefore conclude that this H I signal is most likely associated with the optical galaxy. Additional 21-cm observations on this field are required to confirm this.

In summary, no H I clouds of the type predicted by the BSTHB scenario have been found. Two detections were made that could not unambiguously be identified as known optical galaxies. One is a known tidal H I filament in the NGC 6500/6501 pair, similar to the Magellanic Stream seen in the LG (Putman et al. 1998). The other detection is most likely to be the result of an uncatalogued member of the NGC 5970 group.

5 SPACE DENSITY OF H I CLOUDS

We now use the null result of the Arecibo Group Survey to derive upper limits to the space density of H I clouds in galaxy groups and to discuss the cosmological significance of intragroup H I clouds.

5.1 HVCs as intragroup clouds

An explanation for Galactic HVCs that has widespread current interest is provided by BSTHB who suggest that most of the HVCs are actually distributed throughout the LG and each cloud contains a few $\times 10^7 M_{\odot}$ of H I. We perform Monte Carlo simulations to test this scenario by filling the five observed galaxy groups with synthetic populations of clouds following a recipe outlined by BSTHB. For the cloud properties we use the measured solid angles Ω , velocity widths ΔV , and average brightness temperatures T_B for Galactic HVCs from Wakker & van Woerden (1991). Virial distances r_g are calculated for each cloud individually. The values of r_g are directly proportional to the assumed ratio of baryon to total mass f_B . If f_B is 0.1 , the virial distances r_g are found to be approximately 1 Mpc . At those distances, the distribution of the HVCs is in agreement with the kinematics of the LG, which was one of the main motivations for BSTHB to propose the extragalactic HVC scenario.

Within the groups, the clouds are placed at r_g from the barycentre of the group, in a random direction. This situation would resemble that in the LG, except that the substructure that BSTHB attribute to LG dynamics is not simulated in the models of the external groups. The radial column density distribution for each cloud is first assumed to be flat. The average column density is calculated by taking $\langle N_{\text{H I}} \rangle = M_{\text{H I}} / (\pi r_{\text{cloud}}^2)$, where $M_{\text{H I}}$ is the

cloud H I mass based on its value of r_g and its observed flux, and r_{cloud} is the cloud radius, calculated from its measured solid angle and r_g . For each model, a number of clouds per group, N , is drawn randomly from the Galactic HVC parent population.

The synthetic cloud ensembles are ‘observed’ with patterns of beams following the observational strategy of our survey. A detection is counted if the fraction of the flux of a cloud within the beam exceeds the detection threshold. The simulations are run with velocity resolutions of 5, 10, 25 and 50 km s⁻¹, similar to the search of the real data. The same simulation is run 100 times for each group in order to obtain reliable error estimates on the expected number of detections.

First, we assume that the number of clouds per group, N , is invariant over the different groups. If $N = 100$, which is substantially lower than the number of HVCs observed around the Milky Way Galaxy, the expected total number of detections is 6 ± 3 , where the error indicates the 1σ variation around the mean. Note that N is ≈ 1000 in the BSTHB scenario and ≈ 100 in the BB scenario. The expected number of detections increases linearly with increasing N . Next, we drop the restriction that all groups contain an equal number of clouds and instead scale N with the dynamical mass of the group. This seems like a more logical thing to do since the H I mass and luminosity are also observed to scale in direct proportion to the dynamical mass. However, N could of course be dependent on the dynamical state of the groups. In groups that have formed more recently, the primordial clouds are likely to have been less efficient in merging than in the older groups. We have no detailed information on the dynamical state of the groups, and therefore simply assume that N scales proportional to M_{dyn} . We find that the expected total number of detections rises under this assumption; 23 ± 8 clouds are expected if the number of

clouds in a group with LG mass is $N = 100$. The reason for this increase is that the average M_{dyn} for the external groups is slightly higher than that for the LG.

The conclusion from this exercise is that the hypothesis set forward by BSTHB that HVCs are infalling gas clouds in the LG is highly inconsistent with the observations, unless the LG is an unusual group. If the LG is a representative group and the five surveyed external groups are similar to the LG, our survey should have detected at least 30 clouds (assuming $N = 500$).

5.2 Constraints on intragroup H I cloud properties

A graphical representation of the constraints on intragroup H I clouds is presented in Fig. 3. This figure shows the combined constraints on the mean H I mass of clouds, and the number of clouds in each group. The lines show 68, 90, 95, and 99 per cent confidence levels at which the existence of a cloud population can be excluded. Again we have made use of the observed parameters of Galactic HVCs to model cloud populations in the external groups and the number of clouds N is again scaled with M_{dyn} . For reference, the cloud populations proposed by BSTHB and BB are indicated by hatched boxes, the size of which reflects the uncertainty in the number and average H I mass. The horizontal arrow indicates the effect of changing the mean distance of the BB clouds from 1 Mpc to 650 kpc from the LG barycentre. This latter value was preferred by Braun & Burton (2000) after they had estimated the distance to one HVC by comparing the measured H I column density and the angular size of the cool core. Both the BSTHB and the BB populations are inconsistent with the observations at the >99 per cent confidence level.

The distribution of H I column densities in HVCs often show a core–halo structure (Wakker & van Woerden 1997). Braun & Burton (2000) present high-resolution WSRT imaging of six compact HVCs and show that the morphology can be described by a diffuse halo that encompasses one or more compact cores. We test the influence of this morphology on the detection efficiency in our survey by designing clouds with cores which account for 50 per cent of the total flux and have a radius $R_{\text{core}} = R_{\text{cloud}}/5$. The

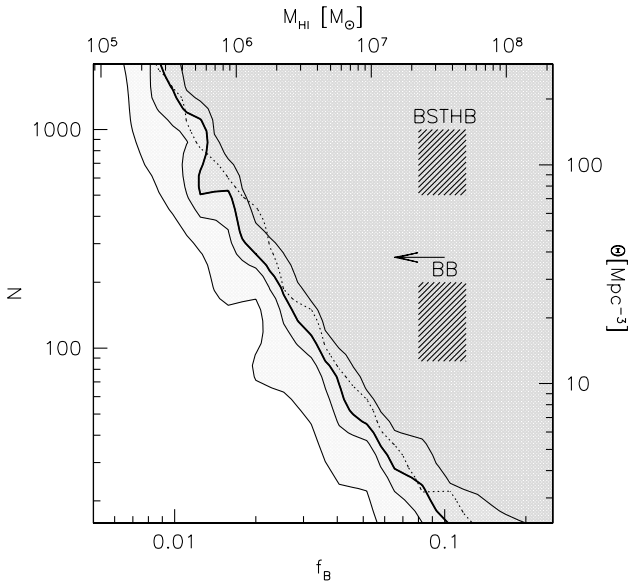


Figure 3. Combined constraint on the baryon fraction f_B and the number of clouds per group N . The number of clouds in each group is normalized using the dynamical mass estimates; the number on the vertical axis is the assumed number in the LG. The average H I masses of the cloud populations are indicated on the top axis. The contours represent 68, 90, 95 (fat line), and 99 per cent confidence levels on the hypothesis that the existence of a group population can be rejected. The dashed line is the 95 per cent confidence level assuming that the clouds can be described by a core–halo model in which 50 per cent of the flux is in a core with a radius of $R_{\text{cloud}}/5$.

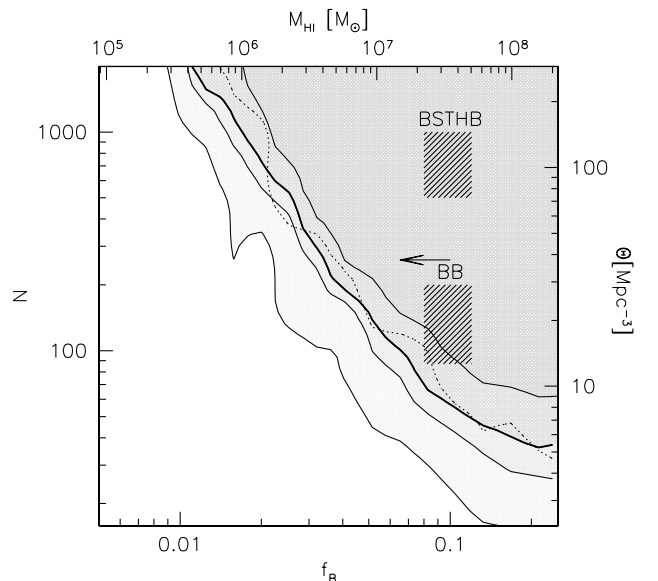


Figure 4. Same as Fig. 3, but here the number of clouds per group, N , is equal for all galaxy groups.

remaining 50 per cent of the flux is distributed over a halo with a flat H I column density distribution. The 95 per cent confidence level on this population is indicated by a dashed line. It is clear that the detection efficiency is not significantly changed by this modification of the cloud structure.

Fig. 4 is similar to Fig. 3, but here the number of clouds per group is non-variant. Again in this case, neither of the proposed population of clouds can be reconciled with our observations.

5.3 Significance of intragroup clouds

How do these upper limits compare to the hierarchical formation scenarios of galaxy groups? Klypin et al. (1999) and Moore et al. (1999) show that in numerical simulations of a hierarchical universe the relative amount of dark-matter substructure haloes is scale invariant. The predicted relative number of dark-matter haloes is similar in clusters, groups and galaxies. However, only in clusters does the predicted number of clumps agree with observed luminosity functions; on galaxies and group scales the simulations predict an excess over the observed number of satellites by a factor of 10, especially for haloes with circular velocities $< 50 \text{ km s}^{-1}$.

One of the proposed solutions for this problem of missing satellites is provided by the BSTHB hypothesis. However, the evidence presented in this paper by Charlton et al. (2000) and by Zwaan & Briggs (2000) seem to rule out this solution. Only a very limited number of clouds with $M_{\text{H I}} \sim 10^7 M_{\odot}$ could exist in galaxy groups. A similar conclusion has been reached by Verheijen et al. (2000), who performed a systematic survey of a region of the Ursa Major cluster of galaxies and found no H I clouds to a limit of $10^7 M_{\odot}$.

From Fig. 3 we conclude that the intragroup H I clouds contribute a maximum of $1.0 \times 10^9 M_{\odot}$ of H I to the total group mass. This implies that no more than 10 per cent of all the H I in groups can reside in clouds with masses greater than $M_{\text{H I}} = 7 \times 10^6 M_{\odot}$. The H I mass in clouds must be less than 0.05 per cent of the total dynamical mass of the groups. In the non-variant N case, these numbers rise to 20 and 0.1 per cent. The dynamical mass of a cloud population that is still permitted by the observations is more difficult to constrain. If we assume that the cold gas (H I and He I) is the only baryonic component in the clouds, and that the baryon fraction $f_{\text{B}} = 0.10$ (a factor normally observed in galaxies and clusters; Fukugita, Hogan & Peebles 1998), then the total contribution of the clouds to the dynamical mass of the groups must be less than 1 per cent. Note that Klypin et al. (1999) estimate that the total mass in the predicted dark-matter satellites amounts to approximately 5 per cent of the total group mass. Such a high prediction can only be brought into agreement with our survey results if the f_{B} of the clouds is lowered to 0.02. However, the median distance of the clouds from the barycentres of the groups would then reduce to $\sim 200 \text{ kpc}$. It is not clear whether this is still consistent with the hierarchical model predictions in which the dark-matter satellites are distributed throughout the groups.

A solution to the problem of missing satellites might be that the cold neutral gas is only a minor contributor to the total baryonic content of the clouds making the H I so insignificant that it cannot be detected in the 21-cm surveys. This situation could occur if a large fraction of the gas reservoirs in the satellites are ionized by the intergalactic background. Klypin et al. (1999) and Moore et al. (1999) discuss gas ejection by early-generation supernova-driven winds and inhibiting gas cooling, and star

formation by photo-evaporation as possible explanations for the absence of cold gas and stars in the satellites.

Solutions of a different kind can be found by changing the predicted number of clouds instead of modifying the baryons within the clouds. This can be achieved by suppressing the primordial density fluctuation spectrum on small scales (Kamionkowski & Liddle 2000). Self-interacting dark matter (e.g. Spergel & Steinhardt 2000) and other dark-matter flavours (fluid dark matter, repulsive dark matter) have been suggested as possible explanations for a less efficient formation of small-mass haloes.

6 SUMMARY

The conclusion reached by Lo & Sargent (1979), that Galactic HVCs are unlikely to be an intergalactic gas in the LG remains sound and intact under scrutiny of a new 21-cm survey with the refurbished Arecibo Telescope. This new survey consists of 300 pointings in five nearby galaxy groups and is sensitive to H I masses of approximately $7 \times 10^6 M_{\odot}$, depending on the velocity spread and distance of the signals. Two detections have been made that are not unambiguously caused by known optically selected galaxies. One is a known tidal H I filament in the NGC 6500/6501 pair, comparable to the Magellanic Stream (Putman et al. 1998). The other detection most likely originates in an uncatalogued member of the NGC 5970 group. We therefore conclude that we have made no significant detections of H I clouds in galaxy groups.

We use this null result to estimate constraints on the proposed population of H I clouds in groups, suggested by Blitz et al. (1999) and Braun & Burton (1999). These authors present a scenario in which the Galactic HVCs are actually distributed throughout the LG at typical distances of a few hundred kpc to 1.5 Mpc. Fig. 3 shows the combined upper limits on the number of clouds per galaxy group, and the average H I mass on such clouds. The Blitz et al. (1999) scenario can be ruled out with > 99 per cent confidence levels, assuming that the LG is typical of the five groups studied here. The integral amount of H I in intragroup clouds is typically less than 10 per cent of the total H I mass of the groups, and less than 0.05 per cent of the total dynamical mass of the groups.

The absence of clouds in groups seems to present a problem for hierarchical structure formation scenarios that predict many satellites within groups. At present it remains unclear as to whether the solution to this problem lies in modifying the descriptions of hierarchical formation so that the predicted number of satellites drops, or that the baryons in the clouds are simply hiding from detection.

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